

Patterns and processes of beach and foredune geomorphic change along a Great Lakes shoreline: Insights from a year-long drone mapping study along Lake Michigan

By

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ABSTRACT

Coastal storms are an important driver of geomorphic change along Great Lakes shorelines. While there is abundant anecdotal evidence for storm impacts in the region, only a handful of studies over the last few decades have quantified them and addressed system morphodynamics. Annual to seasonal lake-level fluctuations and declining winter-ice covers also influence coastal response to storms, yet relationships between hydrodynamics and geomorphology are poorly constrained. Given this, the Great Lakes region lags behind marine coasts in terms of predictive modeling of future coastal change, which is a necessary tool for proactive coastal management. To help close this gap, we conducted a year-long study at a sandy beach-dune system along the western shore of Lake Michigan, evaluating storm impacts under conditions of extremely high water level and absent shorefast ice. Drone-derived beach and dune topography data were used to link geomorphic changes to specific environmental conditions. High water levels throughout the year of study facilitated erosion during relatively minor wave events, enhancing the vulnerability of the system to a large storm in January 2020. This event occurred with no shorefast ice present and anomalously high winter water levels, resulting in widespread erosion and overwash. This resulted in 20% of the total accretion and 66% of the erosion documented at the site over the entire year. Our study highlights the importance of both antecedent and present conditions in determining Great Lakes shoreline vulnerability to storm impacts.

KEYWORDS: UAS, lake level change, Great Lakes, erosion, remote sensing.

*Manuscript submitted 5 March 2021;
revised & accepted 27 April 2021.*

Storms are a primary driver of coastal geomorphic change along the Great Lakes coasts, just as they are along ocean and estuarine coasts. However, while sea level is continuously rising along ocean and estuarine coasts, Great Lakes water levels can fluctuate on the order of meters across annual to decadal timescales (Thompson and Baedke 1995; Quinn 2002). An extended period of below-average water levels was recorded throughout most of the Great Lakes during the 2000s, for example, while periods of above-average levels occurred in the 1970s, 1980s, and from 2013 to present. Water level in the Lake Michigan-Huron basin rose almost 2 m from 2013 to 2020, which is greater in magnitude than the predicted rise in water level for most ocean and estuarine locations within the next century (Cazenave and Le Cozannet 2014). These rapid, high-magnitude water-level fluctuations

represent a considerable management challenge because their timing and coastal impacts are largely unpredictable. This is compounded by an increasing frequency of high-intensity winter storms within the Great Lakes region, based on 20th century data (Angel and Isard 1998). Process-based studies are needed to better understand how specific storm characteristics influence coastal change. This would help planning and future management efforts in the face of ongoing climate change and the accompanying changes in level, storminess, and winter-ice cover.

Lake-level fluctuations shift the zone of wave influence landward (during lake level rise) or lakeward (during lake level fall), which can enhance or mitigate storm impacts (Meadows *et al.* 1997). Storm waves can more easily reach the backshore, foredunes, and even further landward during elevated

base water levels, which generally results in more dramatic coastal geomorphic changes. Coastal infrastructure and ecologically diverse and fragile habitats are particularly vulnerable to damage and erosional losses during these times (e.g. Angel 1995; Braun *et al.* 2019). While beach and foredune recovery can accompany the subsequent fall in lake level from a highstand position, it is important to note that erosive storm events continue to impact the coastal system to varying degrees. While changes may appear less dramatic than those associated with high phases in lake level, they are still likely to play a critical role in setting the geomorphic template for future changes, particularly those of subsequent low-high lake-level transitions.

Another lake-specific hydrodynamic parameter of relevance to coastal processes is the presence or absence of ice, which has a variety of implications for how winter storms impact the coastal system. Some studies show that beaches can be protected from erosion when ice is present along the shoreline, owing to its buffering effect against incoming wave energies (e.g. BaMasoud and Byrne 2012), while others highlight the erosional dynamics of coastal ice in some settings (Barnes *et al.* 1993, 1994). Winter-ice covers have generally declined (in terms of maximum extent and duration) throughout the Great Lakes since 1973, when reliable documentation began (Assel 2005; Wang *et al.* 2012). In

fact, three of the top five lowest ice-cover years for Lake Michigan occurred in the last decade (2010-2020). While ice-cover controls on beach response to winter storms are conceptually understood, no Great Lakes-specific studies have thus far addressed the geomorphic impacts of storms on the coastline during an ice-free winter.

The Great Lakes storm season starts in the fall and ends in the spring. Storm damage reports are generally at their maximum in November and peak once more (albeit slightly lower in magnitude) in April; elevated lake-level conditions exacerbate this trend (Angel 1995). The largest Great Lakes storms tend to occur during the seasonal lake-level decline and/or minimum. However, there are times when lake levels decline only minimally from the annual peak (e.g. the winter of 2020). Seasonal changes in lake level are generally dwarfed in magnitude by annual trends in lake level. Lake Michigan, for example, has been above average water level since 2014, with rates of rise ranging from 7 cm/yr to over 40 cm/yr. Studies are needed to address coastal geomorphic response to storms at varying water-level conditions, given the importance of base (non-storm) water levels on storm response (Angel 1995; Meadows *et al.* 1997).

While anecdotal evidence abounds for storm impacts in the Great Lakes region, few studies address the geomorphic responses of beaches and dunes. Angel (1995) and Meadows *et al.* (1997) show that periods of elevated lake levels are associated with periods of high wave energy, increased coastal damage, and property loss. Prior work in this realm has relied solely on two-dimensional survey information. For instance, Fox and Davis (1973) utilized nearshore profile data to evaluate and predict the general response of the beach and nearshore system to coastal storms. Their study was one of the first and only attempts to document storm response along sandy coastal areas in the Great Lakes region. Others evaluated long-term recovery of beach-dune systems after major storm events (Mathew *et al.* 2010) and addressed linkages between wave climate and potential longshore sediment transport (Davidson-Arnott and Pollard 1980). More recent work has evaluated the role of storms in driving changes in Great Lakes coastal dune (Davidson-Arnott *et al.* 2012; van Dijk

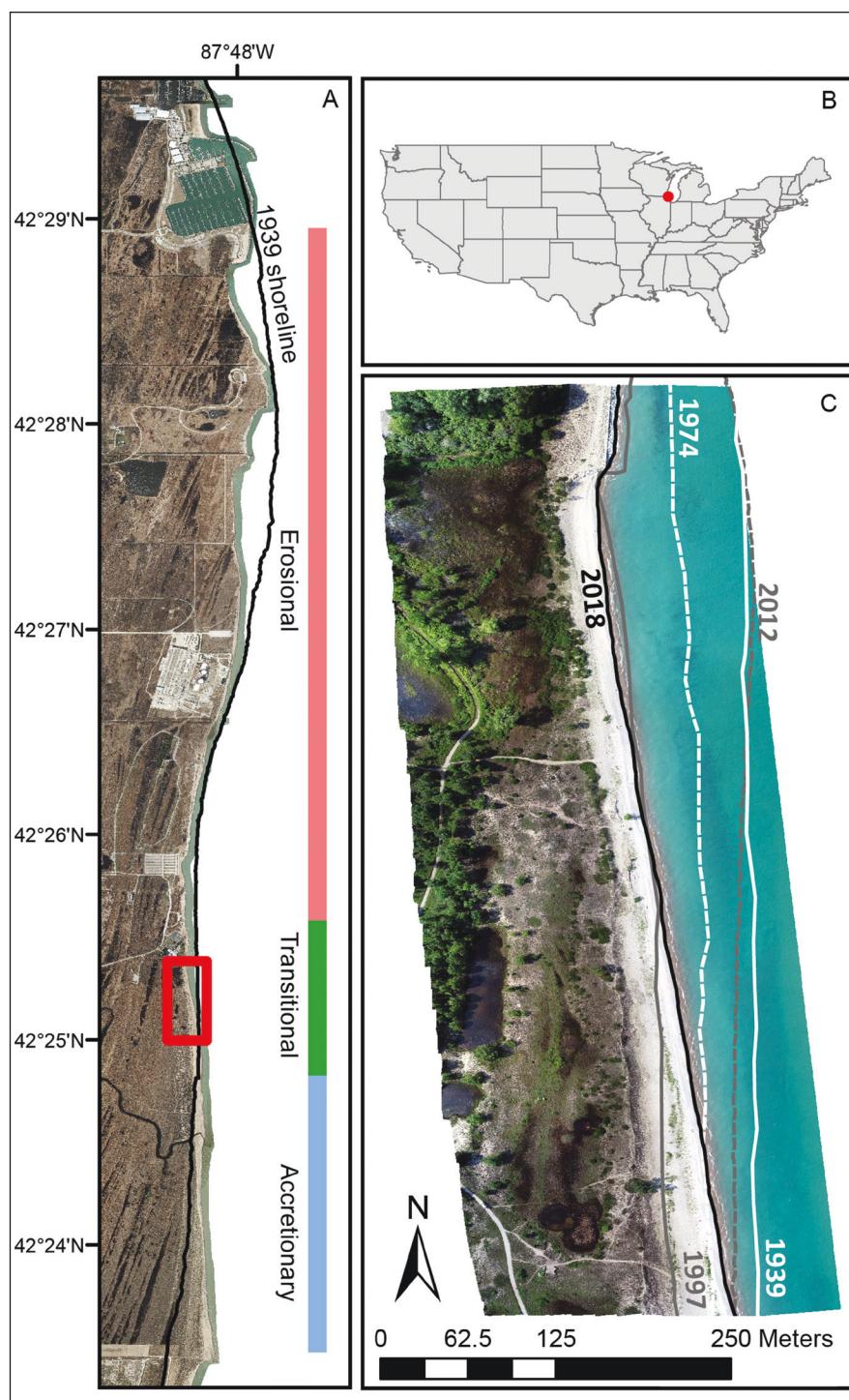


Figure 1. Study area map. A) United States Department of Agriculture NAIP aerial imagery from 2018 showing the Zion Beach-ridge plain. The northern end of the system has a net erosional trend, while the southern end is net accretionary. The study site for this project is located in the transitional zone between erosion and accretion. **B)** The study site is located along the southwestern Lake Michigan coast in Illinois. **C)** Drone imagery collected during this project of the study with historic shorelines from 1939 (white), 1974 (dashed white), 1997 (gray), 2012 (dashed gray), and 2018 (black).

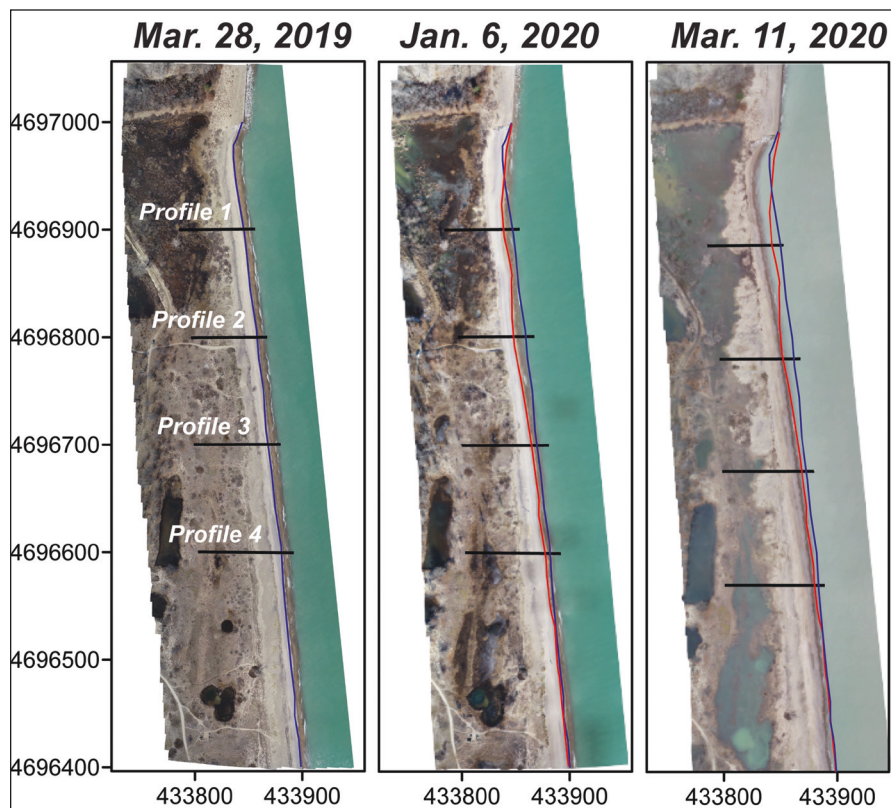


Figure 2. Orthomosaic imagery from the beginning of the study as well as before and after a storm in January 2020. The location of the extracted cross-shore profiles is denoted on each.

2014; Kilibarda and Shillinglaw 2015), coastal bluff (Brown *et al.* 2005, Volpano *et al.* 2020), and nearshore (Greenwood *et al.* 2006) environments. We could find no published studies that quantitatively document major storm impacts on Great Lakes sandy beach systems during a high lake-level year in absence of shore ice. Our lack of process-based knowledge under these base conditions hinders our ability to effectively plan for future storm impacts (under various climate change scenarios) and proactively manage and mitigate coastal hazards in a highly dynamic system.

In this manuscript we present a year of monthly UAS-derived morphology surveys at a beach-dune system along Lake Michigan's wave-dominated southwestern coastal margin. We use these data to address Great Lakes coastal geomorphic response to storm events during ice-free and high decadal lake-level conditions. This study addresses the physical and hydrodynamic drivers of coastal morphology under these base conditions over the course of a full year using repeat UAS survey data. Understanding the temporal context of coastal process-response relationships is needed for coastal decision-making as future climate change is likely

to result in reduced ice covers, increased storm frequencies and intensities, and more rapid fluctuations in lake level (Angel and Isard 1998; Assel *et al.* 2003; Gronewold *et al.* 2013; Mason *et al.* 2016).

METHODS

Study area

The study site, Illinois Beach State Park, is located along the southwestern shore of Lake Michigan, Illinois, USA. It is part of the Zion Beach-ridge Plain, a migratory strand system composed of curvilinear ridges and swales of up to ~3,700 yrs BP in age (in Illinois; Larsen 1985; Figure 1). A southerly net-littoral drift redistributes eroded sediment from the northern portion of the strand to the southern portion. The site of investigation covers 670 m of the transitional portion of the strand, near the node separating historically net-erosional from net-accretionary shoreline portions. Beaches along the studied section are between 10 m and 20 m wide and backed by foredunes on the order of 1.5 m in height. The fore-dune fronts a dune plain characterized by a ridge-and-swale topography, with wetland habitat occupying the latter.

Historical aerial photographs dating as far back as the late 1930s show that the

study area has alternated between periods of stability, accretion, and erosion. Imagery at a near-decadal resolution capture shoreline fluctuations within a ~30 m window between 1939 and 1974 (Figure 1). Shoreline retreat of 20-40 m characterized the 1970s-1990s, followed by an accretionary episode from the late 1990s to 2013 (during an extended low-water phase). Erosion since has been dramatic and the shoreline has retreated between 60 and 100 m between 2014 and 2018 (Figure 1). Shoreline erosion between 2017 and 2018 exposed a sheet-pile wall on the northern end of the site; monthly drone imagery collected since July 2018 shows the shoreline continuing to erode landward immediately down-drift of this armored shoreline. It is important to note that shoreline change in the Great Lakes is not as directly tied to erosion and accretion as it is along oceanic coasts given that substantial movement of a Great Lakes shoreline can result simply from passive inundation or exposure as lake level rises or recedes.

Field methods

A DJI Phantom 4 Pro small Unoccupied Aerial System (sUAS, aka drone) was used to collect high-resolution imagery (better than 0.02 m per pixel) and topography data at the study site. The sUAS is equipped with a 1-inch, 20-megapixel RGB sensor on a gimbal-mounted camera. Flights were flown with consistent parameters (including survey flight lines) using the DJI Ground Station Pro application. Nadir images were acquired at an altitude of 75 m with 90% front overlap and 80% side overlap. Camera position was determined from the onboard GPS/GLONASS satellite positioning system. Ten to 15 ground control points (black and white checkered baseball plates) were positioned evenly throughout the site to account for topographic variances. These points were surveyed with a Trimble Geo7X Centimeter Edition NRTK-GPS with ~0.02 m vertical and horizontal accuracy. Field surveys were only conducted during calm lake conditions (when waves <0.5 m), ensuring that maximum beach areas could be imaged. Monthly to near-monthly surveys (11 in total) were conducted from 28 March 2019 through 11 March 2020.

Morphology data processing

Structure-from-motion photogrammetry was conducted using Agisoft Metashape Professional software. Ortho-

mosaic images and digital elevation models (DEMs) were created from the aerial photographs and RTK-GPS survey data. Ground control point errors of the final DEMs were <0.05 m and checkpoint errors were all <0.1 m. DEMs were exported out of Metashape as ASCII grid files with 0.5 m grid spacings and orthomosaic images were exported as GeoTIFF files at 0.05 m pixel resolution (Figure 2).

The DEMs and orthomosaic images were imported into Golden Software's Surfer for processing and analyses. Because UAS imagery fails to penetrate water and/or thick vegetation, such areas found within the survey bounds were cropped out to leave only the "bare earth" points for analysis. Although most of the thick vegetation (e.g. dense shrub layers) was removed, small and isolated clumps of vegetation (e.g. patches of grass amidst the sand) would remain in the final map products. Care was thus taken to account for such features when interpreting results. A common boundary box was applied to each of the 11 surveys to standardize comparisons. Fully processed DEMs were used to generate DEMs of Difference (DOD) within Surfer, which allowed cross-shore profiles to be extracted for morphologic change analysis. The DODs were used to quantify changes in sediment volume between successive surveys. Only periods with similar vegetation characteristics were compared for volume change analyses (i.e. only winter surveys can be compared to winter surveys). We therefore calculated volume change for the time periods of 28 March 2019 to 6 January 2020 and 6 January 2020 to 11 March 2020. This would also allow us to address the impacts of a large winter storm in January of 2020.

Hydrodynamic data processing

Water-level, wave, and ice-concentration data for the study period were gathered from publicly available datasets. Hourly water-level data from the closest station to Illinois Beach State Park (Milwaukee, WI — Station ID: 9087057) were downloaded from the National Oceanic and Atmospheric Administration (NOAA) Tides and Currents site (Figure 3). These data are reported in meters relative to the vertical datum IGLD85 and had to be converted into NAVD88 (conversion factor of +0.166 m) to ensure a common vertical datum with our topographic data. Modeled significant

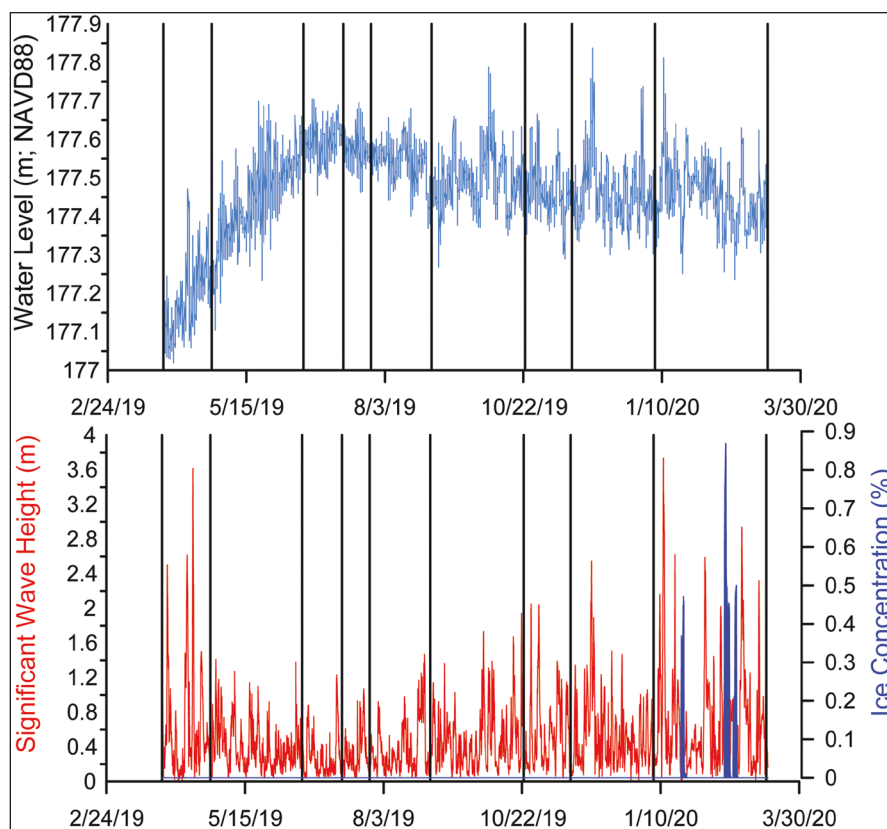


Figure 3. (Top) Water level data from the Milwaukee water level station. Dates of surveys are denoted with black lines. (Bottom) Significant wave height data (red) and ice concentration data (blue) from the Great Lakes Coastal Forecasting System model. Data was provided by GLERL for the grid node closest to the study area.

wave-height and ice-concentration data from the Great Lakes Coastal Forecasting System were provided by the Great Lakes Environmental Research Laboratory (National Oceanic and Atmospheric Administration Great Lakes Environmental Research Laboratory 2019). Reported RMSE is less than 0.25m for comparisons of the modeled wave height data to National Data Buoy Center observations (National Oceanic and Atmospheric Administration Great Lakes Environmental Research Laboratory 2020). This information was used in lieu of in situ observations from nearby buoys as model data provide a continuous time series for the period of study. Buoy data, for instance, only cover April through November, thus omitting the critical winter-storm period.

A variety of metrics were generated from the hydrodynamic data to characterize the conditions during each interval between surveys (Table 1). In order to identify periods of increased storm activity, the percent of onshore significant wave heights above 2 m was calculated (Table 1). Long-term storm datasets for the Great Lakes have defined

storm waves as having significant heights greater than 2 m (Hubertz 1992). Average and maximum lake levels were tabulated for each of the survey intervals in order to document seasonal and annual trends and to identify periods when lake levels exceeded the monthly average (within each survey interval). The details of individual storm events (i.e. waves above 2 m for greater than two hours), including the duration of the event, the maximum wave height, and the maximum water level were noted (as was percent ice cover for each survey interval).

RESULTS

Hydrodynamics

Wave, water-level, and ice data were used to identify the dominant drivers of change for each survey interval (Figure 3; Table 1). Lake level was above the long-term average (~176.5 IGLD85 meters) throughout the duration of study (Table 1). Average lake level for each survey interval followed the general seasonal trend of rising during the spring, peaking in mid-summer, and falling in late summer and fall. Water level rose rapidly during spring 2019 (beginning of

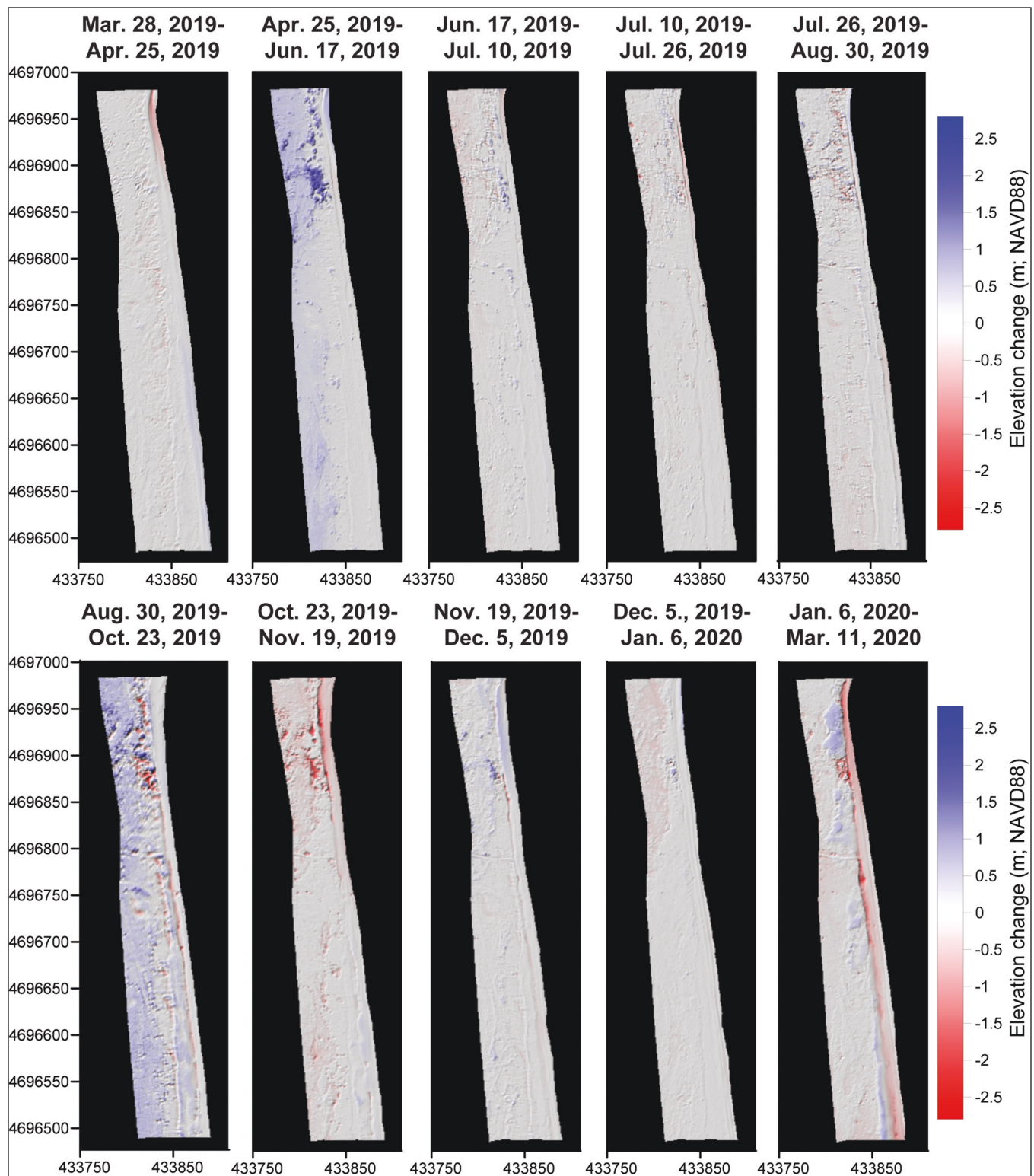


Figure 4. DEMs of Difference (DOD) generated using drone-based topography data for each survey interval examined in this study. Areas in red denote erosion and areas in blue denote accretion. Note that during some time periods the most landward areas are recording vegetation change rather than topography change. None of these time periods were used for volume change estimates for this reason and profiles were extracted away from these vegetation growth hotspots.

the study) due to high precipitation and runoff relative to evaporation throughout the winter and spring of 2019. Maximum lake levels ranged from 11 cm above average to in excess of 30 cm above average (Table 1). The lowest maximum levels occurred from June 2019 through August 2019, in absence of storm events. Maximum water levels ranged from 20 to 30 cm above average during survey intervals with recorded storms. While not direct measures of storm-surge height, these metrics reflect the superelevation of water levels during high-energy events.

The percentage of waves above 2 m during each survey interval was used as a metric for relative storminess (Table 1). From 25 April 2019 through 23 October 2019, no waves >2 m in height were recorded (Figure 3; Table 1). The same was the case for 5 December 2019 through 6 January 2020. A total of four survey intervals during the year-long study recorded wave heights >2 m, the greatest percentage of which fell between 28 March and 25 April of 2019 (6.3%). This was followed by 6 January through 11 March of 2020 (4.6%), 19 November through 5 December of 2019 (3.9%), and 23 October through 19 November of 2019 (0.5%).

Ice-cover data derived from the GLERL Nowcast model indicate absence of ice over nearly the entire timeframe of study (Figure 3). The first detection of ice at the study area, according to GLERL data, was on 21 January 2020. Only ~21% of the hourly ice-concentration data between then and 11 March 2020, indicated ice presence. Trail cameras deployed at the site confirmed the lack of ice during the storm events studied.

Table 1.
Hydrodynamic metrics for each of the survey intervals.

	Percentage of waves above 2m	Maximum wave height (m)	Average lake level (m; NAVD88)	Maximum lake level (m; NAVD88)	Difference between max. and average during interval (m; NAVD88)
28 March 2019-25 April 2019	6.3	3.6	177.2	177.5	0.3
25 April 2019-17 June 2019	0.0	1.4	177.4	177.7	0.3
17 June 2019-10 July 2019	0.0	1.2	177.6	177.7	0.1
10 July 2019-26 July 2019	0.0	1.1	177.6	177.7	0.1
26 July 2019-30 August 2019	0.0	1.5	177.5	177.7	0.1
30 August 2019-23 October 2019	0.0	1.9	177.5	177.8	0.3
23 October 2019-19 November 2019	0.5	2.1	177.5	177.7	0.2
19 November 2019-5 December 2019	3.9	2.5	177.5	177.8	0.3
5 December 2019-6 January 2020	0.0	1.5	177.4	177.7	0.3
6 January 2020-11 March 2020	4.6	3.7	177.5	177.8	0.4

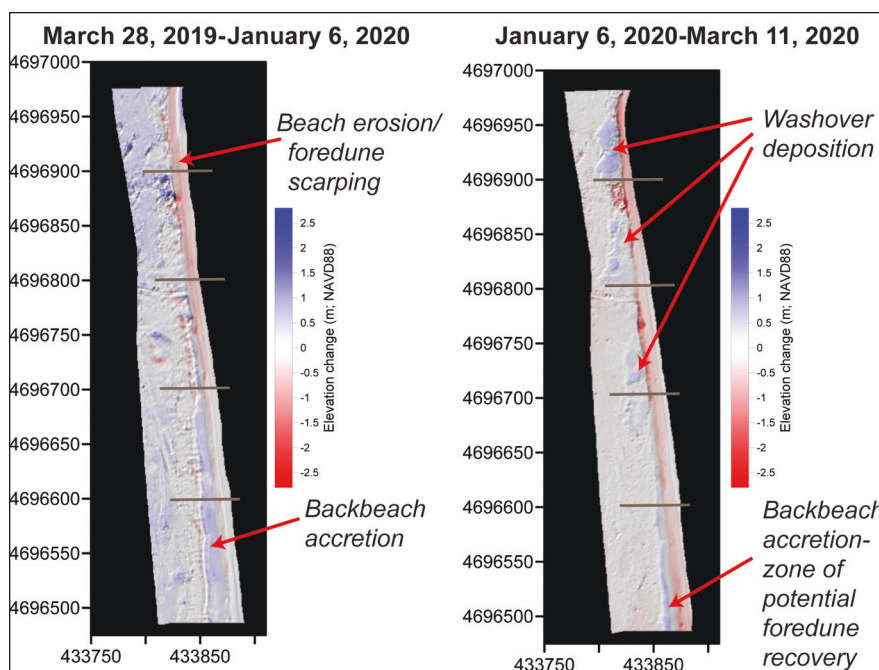


Figure 5. DOD comparison of change prior to the large storm in January and the change resulting from the large storm. The locations of the cross-shore profiles are denoted on this graphic in brown and follow the same nomenclature as in Figure 2.

Lakewide data from GLERL indicate that the winter of 2020 had the second lowest average percentage ice cover on record (i.e. since 1973).

While the wave, water level, and ice data presented above provide an overall sense of our survey conditions, it is important to further investigate the specific conditions during each of the five individual storm events for which wave heights >2 m. Three of these events occurred in rapid succession between March and April of 2019. Only two storm events were recorded during the fall and winter of 2019-2020. The details of these storms are provided in Table 2.

Morphology change

Spatiotemporal variability in beach and dune morphology was evaluated using a combination of DODs and two-dimensional cross-shore profiles. The DODs provide insight into spatial patterns of erosion and accretion throughout the site between surveys (Figures 4 and 5). These maps and derivative volume-change metrics are to be interpreted critically as structure-from-motion photogrammetry only works well to generate topographic information on unvegetated or sparsely vegetated surfaces. If vegetation is present or if growth or die-back occurs in an area between surveys, then the DOD

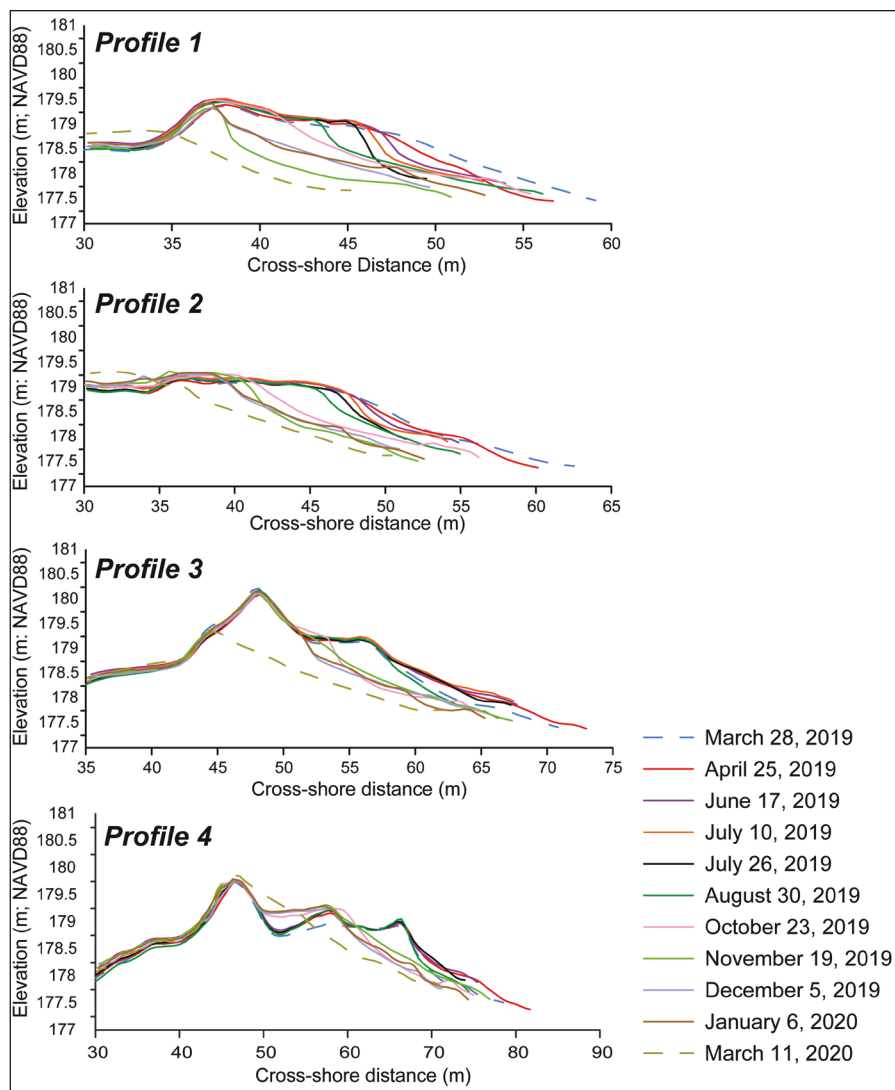


Figure 6. Cross-shore profiles documenting morphology changes throughout the year and in response to the January storm. The first and last surveys are highlighted with a dashed line to highlight the resultant morphology.

will show change that is unrelated to sedimentary changes (both erosional and/or depositional). Shore-normal transects were therefore extracted from the survey DEMs along four vegetation-free site locations to evaluate how beach and dune morphology evolve in response to wave events and changes in water level (Figure 2).

Minimal change was observed in the 28 March to 25 April 2019 DOD (Figure 4). Foreshore and backshore erosion were documented along an ~75 m stretch of beach at the northern end of the site, just downdrift from a seawall and revetment. Slight accretion was observed along the beach at the southern end of the site. These changes are largely attributed to three storms. Accretion along the formerly erosive stretch of beach (the previous timestep) was documented

between 25 April and 17 June 2019. Vegetative growth occurred landward of the foredune, manifested as apparent accretion in the DOD. Minor beach erosion was resolved at the very northern end of the site from 17 June to 10 July 2019. Backshore erosion and foredune scarping dominated the northern end of the site from 10 July through 26 July 2019, while minor foredune erosion and some slight foreshore accretion were recognized along the northern quarter of the site from 26 July through 30 August 2019. The zone of foredune erosion shifted to the southern half of the site from 30 August to 23 October 2019, for which time significant vegetational changes are also seen in the DODs.

Additional foredune erosion was documented along the northern half of the study area as the fall and winter

storm season began, as seen in the 23 October through 19 November 2019 DOD (Figure 4). Backshore and foreshore accretion were observed from 19 November through 5 December 2019 at the far northern end of the site. Minor foredune erosion occurred at isolated locations throughout the rest of the site. Much of the change is attributed to the 30 November to 1 December storm event. No change was detected across most of the site from 5 December 2019 to 6 January 2020. However, dramatic changes occurred over the period spanning 6 January to 11 March 2020, as extensive beach and foredune erosion and associated washover and backshore accretion were recognized (Figures 4 and 5). These geomorphic changes are attributed to the 11–12 January storm. No later wave events were documented after this event, and shore ice formed shortly thereafter, protecting the beach from erosion.

From 28 March 2019 to 6 January 2020, net volume change along this site was 3,321 m³ with 6,271 m³ of accretion and 2,949 m³ of erosion. From 6 January 2020 to 11 March 2020, net volume change was -4,220 m³, with 1,454 m³ of accretion and 5,675 m³ of erosion. Our data indicate that ~20% of the total accretion and 66% of the erosion experienced by the site over the survey period resulted from the January storm.

Changes in the cross-shore profiles over the one-year timeframe of study provide additional insights on specific morphologic changes (Figure 6). These data also highlight the high degree of spatiotemporal variability in geomorphic change and vulnerability to specific events. Generally, overall profile elevations appeared to be less important than foreshore and backshore widths in dictating magnitudes of change.

Beach erosion was observed between 28 March and 25 April 2019, at the northernmost profiles (1 and 2; Figure 6). This time period experienced three storm events within a two-week window. The therewith associated erosion was concentrated on the foreshore along Profile 1, but impacted both backshore and foreshore along Profile 2. Further south, accretion during this period was documented across the foreshore (Profile 3) and both the foreshore and backshore (Profile 4). These sedimentary patterns

may reflect erosion and transport from northern to southern portions of the study site by way of littoral drift. Profiles 1 and 2 experienced additional beach erosion during the period from 25 April to 17 June 2019, which resulted in a scarped berm. Minimal profile change was documented at Profiles 3 and 4 (the southernmost) during this period. This pattern of minimal change would persist here through 26 July 2019. From 17 June through 30 August 2019, erosion continued at Profiles 1 and 2, manifesting in the progressive landward translation of berm scarping and beach narrowing. Foreshore erosion at Profiles 3 and 4 during this time began to increase and both profiles re-equilibrated to their starting positions (March 2019).

From 30 August to 23 October 2019, all of the profiles experienced foreshore erosion and scarping (Figure 6). Profiles 3 and 4 experienced backshore accretion most likely induced by runup overwash. However, it may also have resulted from foredune erosion and slumping. No storms occurred during this time period and documented erosion and overwash are likely attributable to high water levels. Maximum water level during this time span was 29 cm above the monthly average, allowing waves of lesser size to impact areas further up the beach face. Profile 4 translated landward during this phase after several months of relative stability.

More erosion was documented from 23 October through 19 November 2019, despite absence of major storm events (and a maximum wave height during this period of 2.05 m). The foredune began to erode at Profiles 1 and 2 at this time, becoming scarped, and the entire beach profile underwent noticeable deflation (Figure 6). Profiles 3 and 4, on the other hand, accreted during this time, albeit to varying degrees and spatial patterns. The material deposited at the base of the foredune in Profile 3 during the previous timespan was eroded away while the portion of the profile formerly scoured underwent accretion. Positive changes in backshore and foreshore elevation were observed at Profile 4. However, the berm crest migrated landward by several meters.

The late November/early December storm event resulted in variable profile changes. Accretion was observed across

Table 2.
Hydrodynamic metrics for the storm events during this study.

Date of storm	Duration of storm	Maximum wave height	Maximum water level	Elevation of water above survey interval average
30-31 March 2019	7 hours	2.5 m	177.2 m	10 cm
11 April 2019	15 hours	2.6 m	177.4 m	26 cm
14-15 April 2019	14 hours	3.6 m	177.3 m	11 cm
30 Nov.-1 Dec. 2019	14 hours	2.5 m	177.8 m	30 cm
11-12 January 2020	22 hours	3.7 m	177.8 m	35 cm

the beach along Profiles 1 and 2 (Figure 6). This contrasts the general trend of erosion characterizing most of the terrain throughout prior surveys. Foredune erosion was documented at Profile 2, but no change in the foredune morphology occurred at Profile 1. Beach erosion was observed at Profiles 3 and 4, with scarping of the foredune base at the latter. All sites changed minimally from 5 December 2019, through 6 January 2020 with the exception of bars welding to the lower foreshore at each of the profiles.

The most dramatic changes in morphology during our year-long study were observed between 6 January and 11 March 2020, in response to the 11-12 January storm (Figure 6). Foredune and beach erosion as well as landward translation of the profile were documented across Profiles 1, 2, and 3. Foredunes were leveled, and the beach profiles were deflated and translated landward. Some of the foredune material wound up in washover landward of the original foredune crests at profiles 1 and 2. No overwash occurred at Profile 3, but the close to 1 m-lowering of the dune crest height here will likely facilitate such in the future. Continued overwash at Profile 1 is now even more likely as the maximum profile elevation on 11 March 2020 is around 0.5 m lower than those elsewhere. No foredune erosion was documented at Profile 4. However, the entire beach profile translated landward. Prior to this event, this location was characterized by the widest beach (of the four profiles examined), characterized by a well-developed berm and backshore. These were eroded by the storm and sand was deposited at the base of the foredune. Lower magnitude changes at Profile 4, relative to the other profile locations, likely reflects a combination of previously wide beach and potential influx of eroded material from updrift foredune erosion.

DISCUSSION

This study puts forth a dataset that places geomorphic changes resulting from a large winter storm event into context of broader morphologic changes over a year of high lake levels and limited ice cover. Substantial spatial and temporal variability in beach and dune morphologic change was documented along the less than 1 km stretch of shoreline. At the beginning of the study, when lake level was its lowest, a trio of storms occurred within a two-week window. The portion of the study site immediately downdrift of the armored shoreline bordering it to the north eroded in response to these events. Areas further south did not, but rather accreted slightly, likely due to littoral drift deposition of sands eroded to the north.

As lake level rose over the subsequent months, erosion dominated the northern half of the site and the beach widths narrowed. Studies of similar shoreline sections along the Illinois Beach State Park shoreline also capture this tight temporal coupling between seasonal lake-level rise, coastal erosion, and profile retreat (Theuerkauf *et al.* 2019). The southern end of our survey site during this time experienced minimal net change, likely due to the influx of eroded material from the updrift portion by way of littoral drift. By the time lake level reaches the annual peak (July 2019) the influx of material from littoral drift either slows or is not enough to compensate for enhanced erosion due to high lake levels, thus erosion is documented across the entire site. The most severe erosion, however, still occurred immediately downdrift of the shore protection structure bounding the survey area to the north.

Substantial erosion and profile retreat occurred at all sites from 30 August through 23 October, although no storm events were recorded during this period.

This may be attributed to a high water-level period in early October (2-4), which exceeded the average monthly mean for several days and peaked at a maximum just under 30 cm above the former. The seasonal rise in lake level plus this brief rise in water level in early fall increased site vulnerability to fall storms.

Beach erosion, which included foredune scarping, was observed throughout most of the site during the stormy fall season (October through December of 2019). Only one storm event stands out during this period (30 November-1 December), during which most of the site experienced backshore erosion and the foreshore either accreted or showed no change. The northern portion of the site (Profile 1) accreted in response to this storm, likely facilitated by waves approaching the shoreline from the southeast. The resulting northward flow of the longshore current (counter to prevailing trends) deposited material along the site's northern portion (in the lee of the hardened shoreline that ordinarily promotes wave refraction and enhanced erosion here). Alternatively, given the high lake level and increased wave energy material could have been eroded from the backshore and deposited along the foreshore during this event.

Quiet wave conditions prevailed from 19 December to 6 January, with the entire site experiencing minimal change. Bars were observed to have welded to the foreshore along most of the site during this time, suggesting beach recovery was beginning despite the continuation of high water levels (at ~10 cm below the seasonal peak; typical changes are around 25 cm).

The 11-12 January 2020 storm caused major geomorphic changes that would alter the evolutionary trajectory of the site. Prior to this event, the southern half of the study area had experienced significant backshore accretion. If left undisturbed, this would have likely promoted foredune development, particularly during an average year with typical seasonal lake-level patterns and presence of shore ice as winter storm-wave buffer. However, the erosion of these materials by storm waves changed the existing foredune morphology.

There was no lowering of the foredune crest elevation in the far southern end of the site (Profile 4), given a wide beach

and more topographically pronounced foredune. This contrasts with the area immediately to the north (Profile 3), where the beach had significantly narrowed before the storm. This area was consequently more vulnerable to the storm's impacts and thus experienced foredune erosion and crest lowering. Recovery of the foredune is likely in the southern area, where its crest did not undergo loss and where sand was deposited at its base (likely by wave runoff).

The morphologic changes along the northern half of the site during the months leading up to the storm set the stage for subsequent storm impacts. Overall, the area was lower in elevation than the southern half of the site and lacked a well-developed foredune. This morphology coupled with the sustained narrowing of the beach from erosion throughout the preceding months increased site vulnerability. Additionally, its position immediately downdrift of the hardened shoreline likely enhanced erosional scour during the storm, which was distinctly resolved in the DOD (Figure 5). Significant erosion and overwash were documented in response to the storm along these narrow and low elevation portions of the site. Foredunes, where present, were leveled by the storm surge and waves. Most of the foredune material was likely deposited in the washover terraces, although some appears to have been removed and transported away by longshore currents.

The January 2020 storm created much of the annual net change at our study site, setting the template for its continued evolution. If annual lake levels begin to trend downward, existing foredunes may fully recover and washover deposits may evolve into new ones. If lake levels rise, then the spatiotemporal patterns documented in this study will likely result in more erosion and overwash. While beach and foredune erosion (i.e. beach-profile narrowing) of the preceding months made the site more vulnerable to storm impacts, the conditions of sustained high water and lack of winter-ice cover likely facilitated the major geomorphic changes observed. The volume-change data suggest that 20% of the total accretion and 66% of the total erosion documented at this site throughout the year resulted from the single January event. These findings highlight the importance of antecedent

morphology, in addition to water level and ice conditions for dictating storm vulnerability.

CONCLUSIONS

The results of this study highlight the important role of high water levels and antecedent morphologic conditions in dictating site vulnerability from specific storm events. The documented geomorphic changes that occurred along the site during the summer and fall of 2019 in response to sustained high water levels set the stage for major impacts to the site during the January 2020 storm. Furthermore, the January 2020 storm was unique in that it occurred during a period of anomalously high winter water level and complete absence of shorefast ice. These conditions coupled with the site vulnerability from prior conditions led to this event generating more erosion than was documented at the site throughout the entire year.

While this study focused on a small stretch of the wave-dominated SW Lake Michigan coast, our results are applicable to other sandy shoreline areas of the Great Lakes, particularly those of similar geomorphology found immediately downdrift of hardened shorelines. The dynamic changes captured prior to the storm and those resulting from it highlight the need for more long-term monitoring efforts along sandy coastlines of the Great Lakes. Our study helps fill the data and knowledge gaps pertaining to Great Lakes storm geomorphology. Additional process-based studies are needed to inform our evolving understanding of near-shore morphodynamics across a variety of coastal settings, including bluff shorelines, coastal wetlands, and engineered coasts.

ACKNOWLEDGEMENTS

We thank Kevin Engelbert and Cesar Gutierrez for help with fieldwork and processing of sUAS data. Funding for this project was provided by the Great Lakes Restoration Initiative through a grant from the National Oceanic and Atmospheric Administration; the Illinois Department of Natural Resources Coastal Management Program; and the National Science Foundation (Award Number: 1950101- Collaborative Research: Sediment Transport Mechanisms and Geomorphic Processes Associated with Shore Ice along Cold Climate Coastlines). The authors declare that there are no conflicts of interest.

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